Dynamical Decoupling of Crosstalk on Superconducting Qubit Devices

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Motivation

- NISQ era: living with errors in quantum computers.
  - Error mitigation needed to reach threshold for error correction.
- Dynamical decoupling (DD):
  - Loop free error suppression – no feedback involved.
  - Long track record, proven ability to improve fidelity in many types of devices (superconducting, NMR, trapped atoms/ions…).
- DD key idea: apply periodic pulse sequence to qubit(s). Average out:
  - Decoherence for single qubit.
  - Undesired couplings between pairs of qubits.
- Based on spin echo effect.

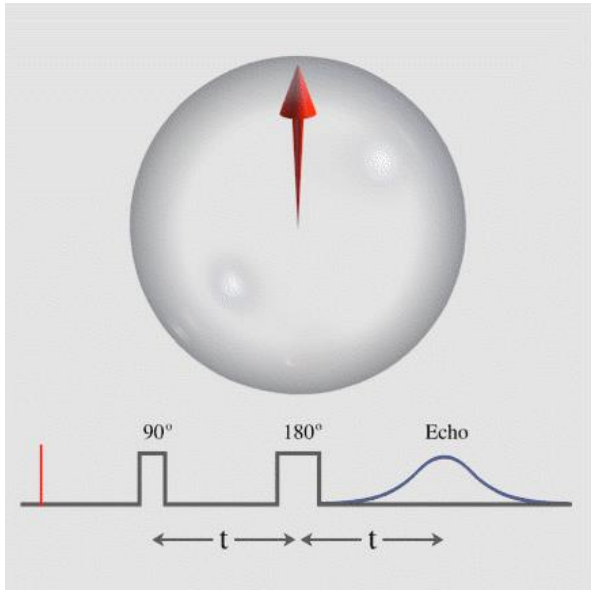
CROSSTALK

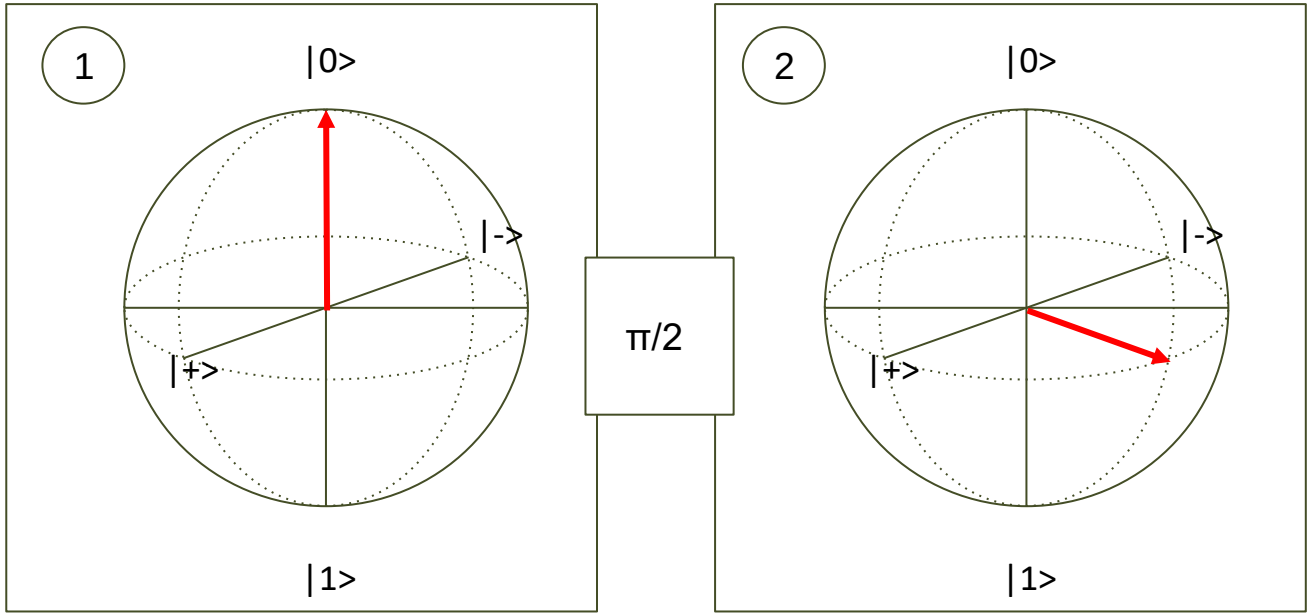
Umbrella term for many types of unwanted interaction.
Hardware dependent.
Noxious effects at the logical quantum level.

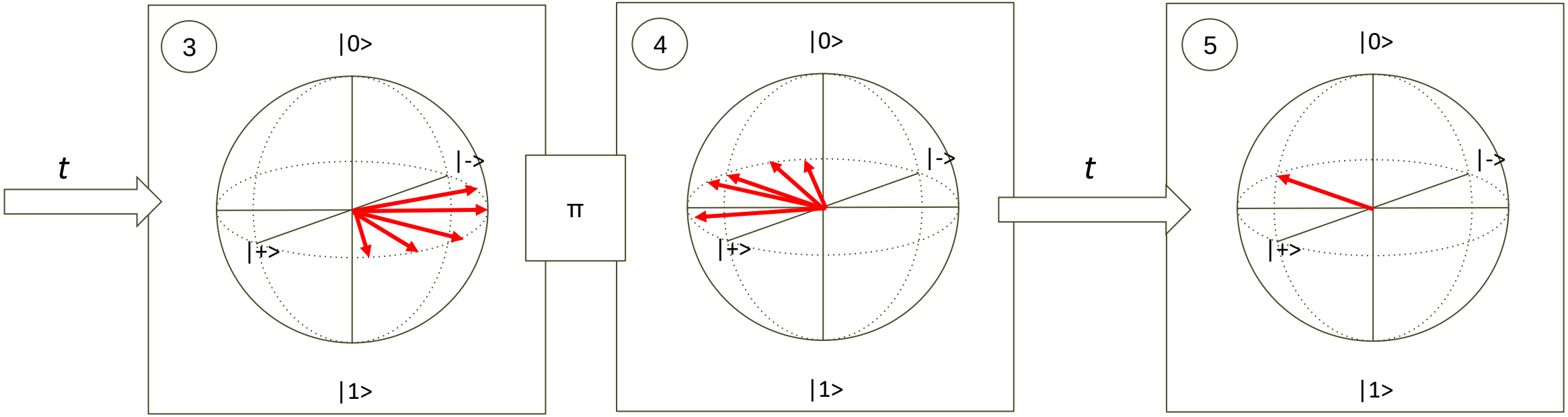
ZZ COUPLING

Major component of crosstalk for superconducting qubit devices.
Two qubits couple to a fluctuating magnetic field, leading to correlated dephasing.

Spin echo

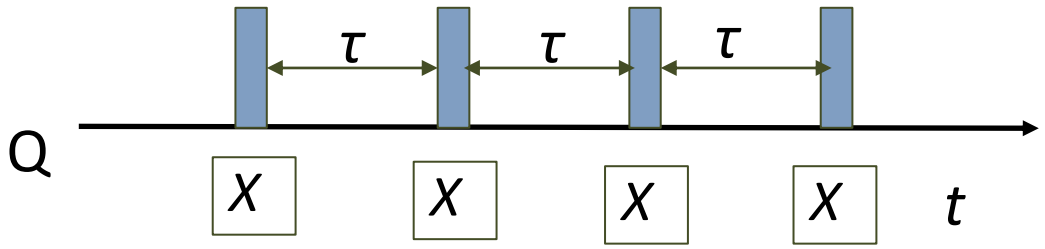






Dynamical Decoupling

THE ART OF SEQUENCE DESIGN



Example of a typical DD sequence (XXXX)

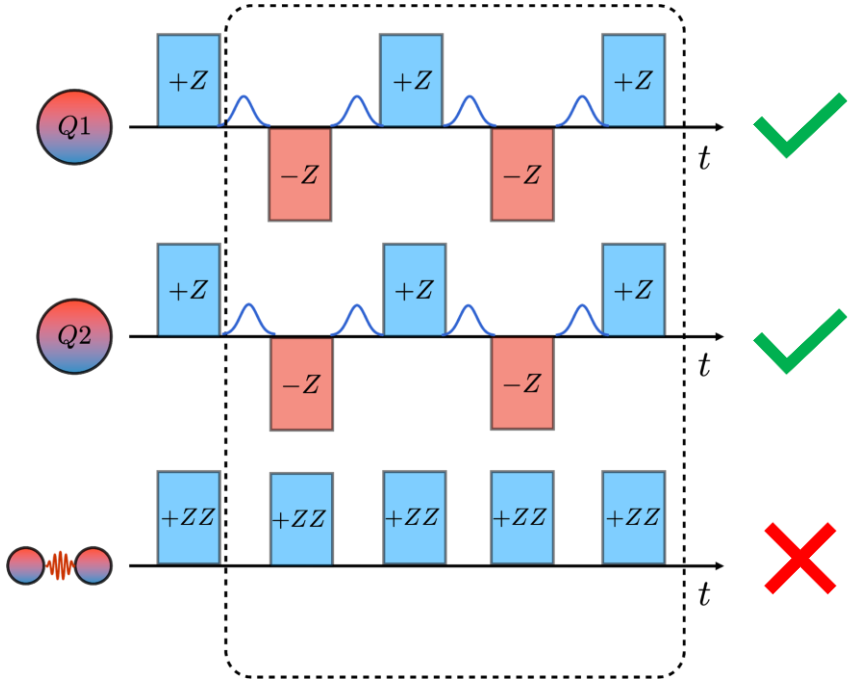
- For short repetition periods of a sequence of pulses, the system behaves as though acting under the time-averaged Hamiltonian.
- Longer sequences work better, but pulse error accumulation comes into play.

- Design of effective DD sequences must involve hardware-specific considerations.
  - What error channels are present?
  - What pulses can we produce?
  - What is our level of individual qubit control?

Standard DD sequences

AND WHY THEY CANNOT SOLVE ALL OUR PROBLEMS...

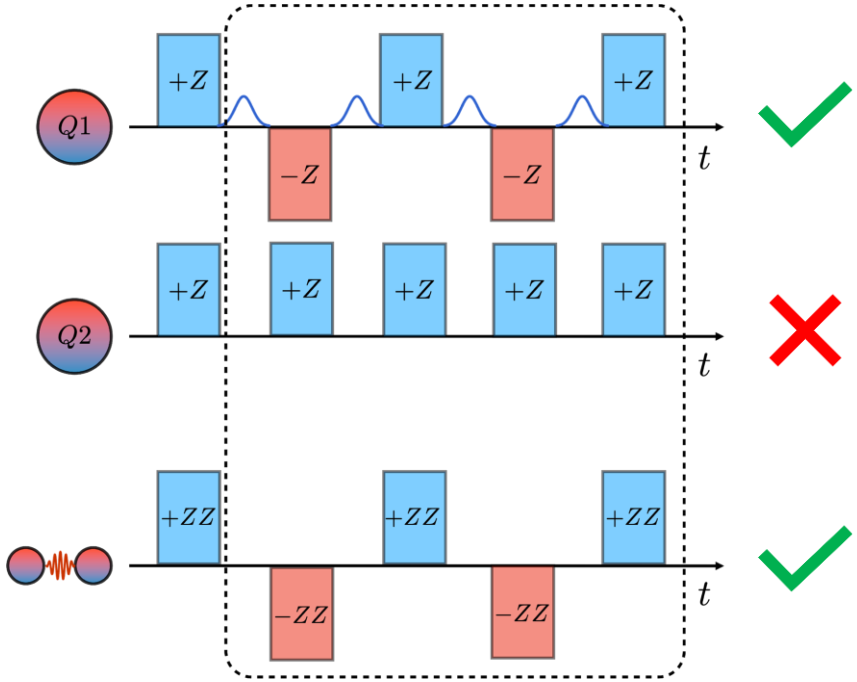
Same sequence applied to both qubits suppresses individual decoherence, but ZZ coupling remains.



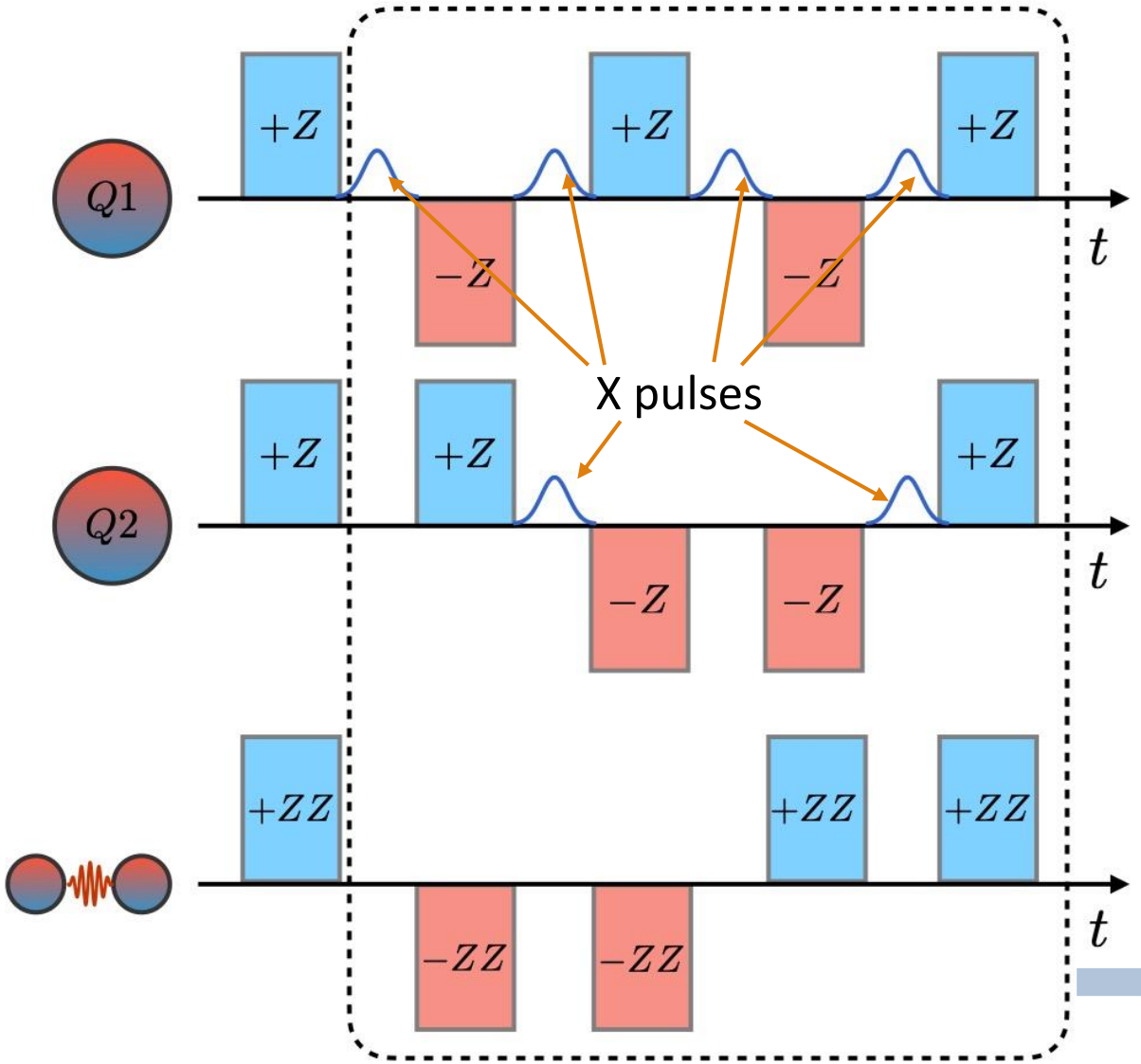
ZZ coupling is the main component of crosstalk - we want to decouple it.

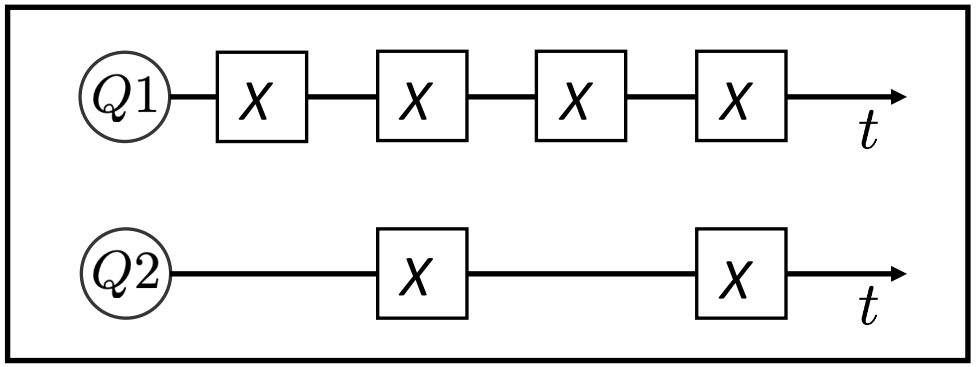
But not at the expense of one of our qubits.

DD on one qubit only might cancel out ZZ, but does nothing for the second qubit's decoherence.



Frequency mismatching





WHAT'S NEW?

A frequency-mismatched DD sequence such as (XXXX, XX) can decouple ZZ interactions without sacrificing either individual qubit.

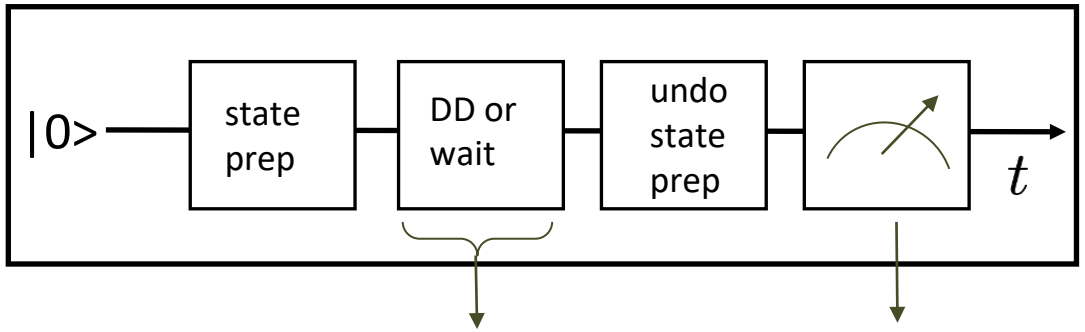
ZZ coupling averages to zero after each FM DD sequence.

Results: single qubit

Experiments performed on Rigetti Aspen-M-2 chip

DD has extensively been shown to improve coherence of isolated qubits. We start by verifying this.

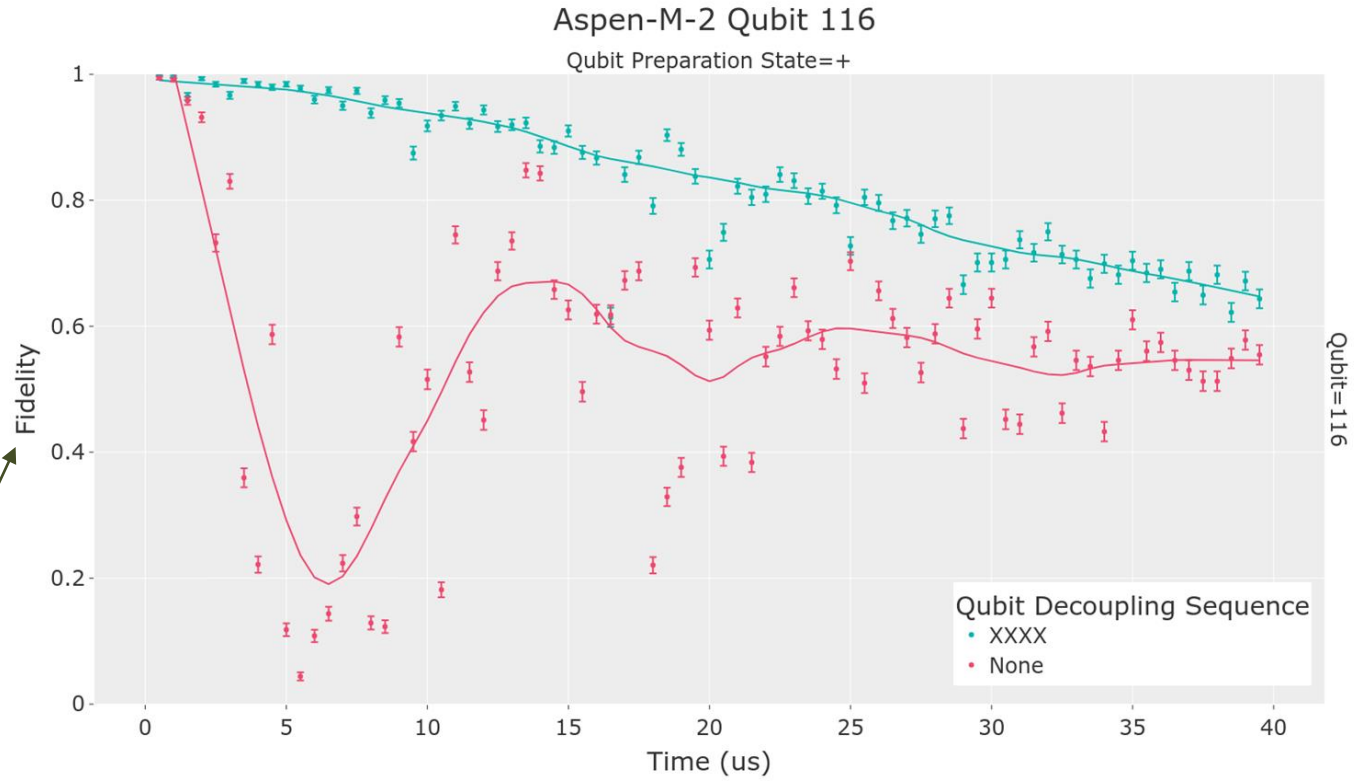
EXPERIMENTAL CIRCUIT



Repeat some number of times

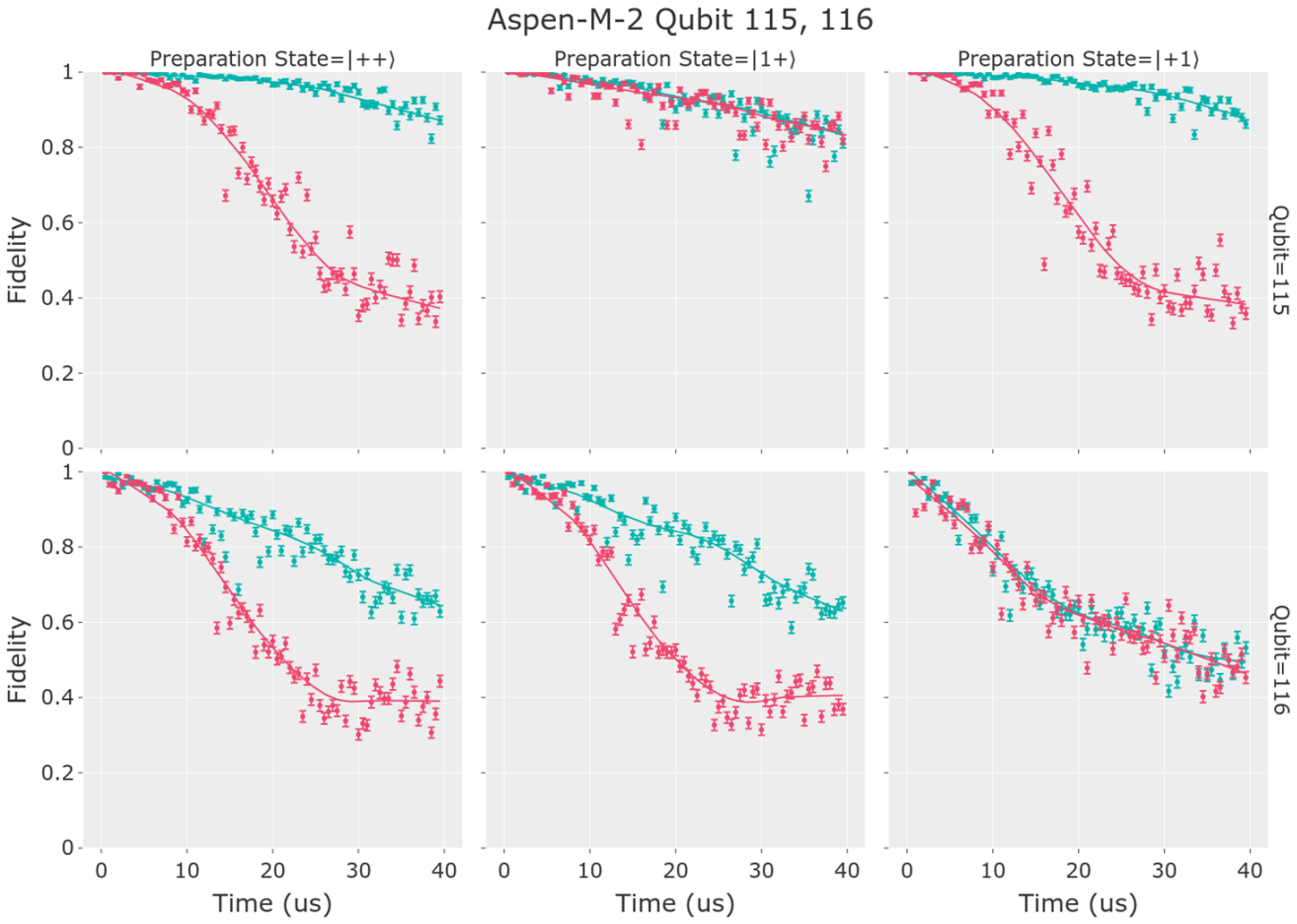
Report overlap with |0>

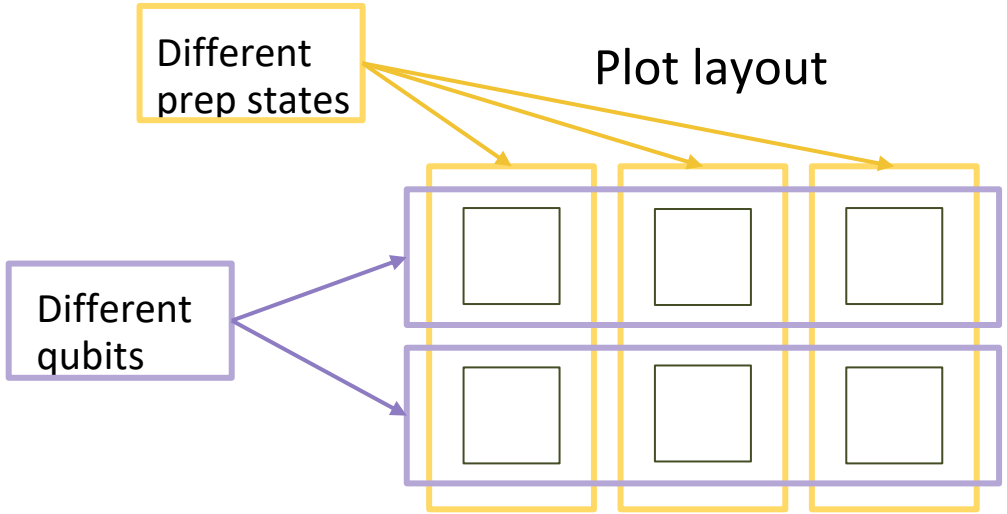
Single-qubit fidelity



Effectiveness of targeting ZZ crosstalk with DD

- Synchronized (XXXX, XXXX): decoupling single qubit interference
- Frequency mismatched (XX, XXXX): decoupling both single qubit and ZZ coupling

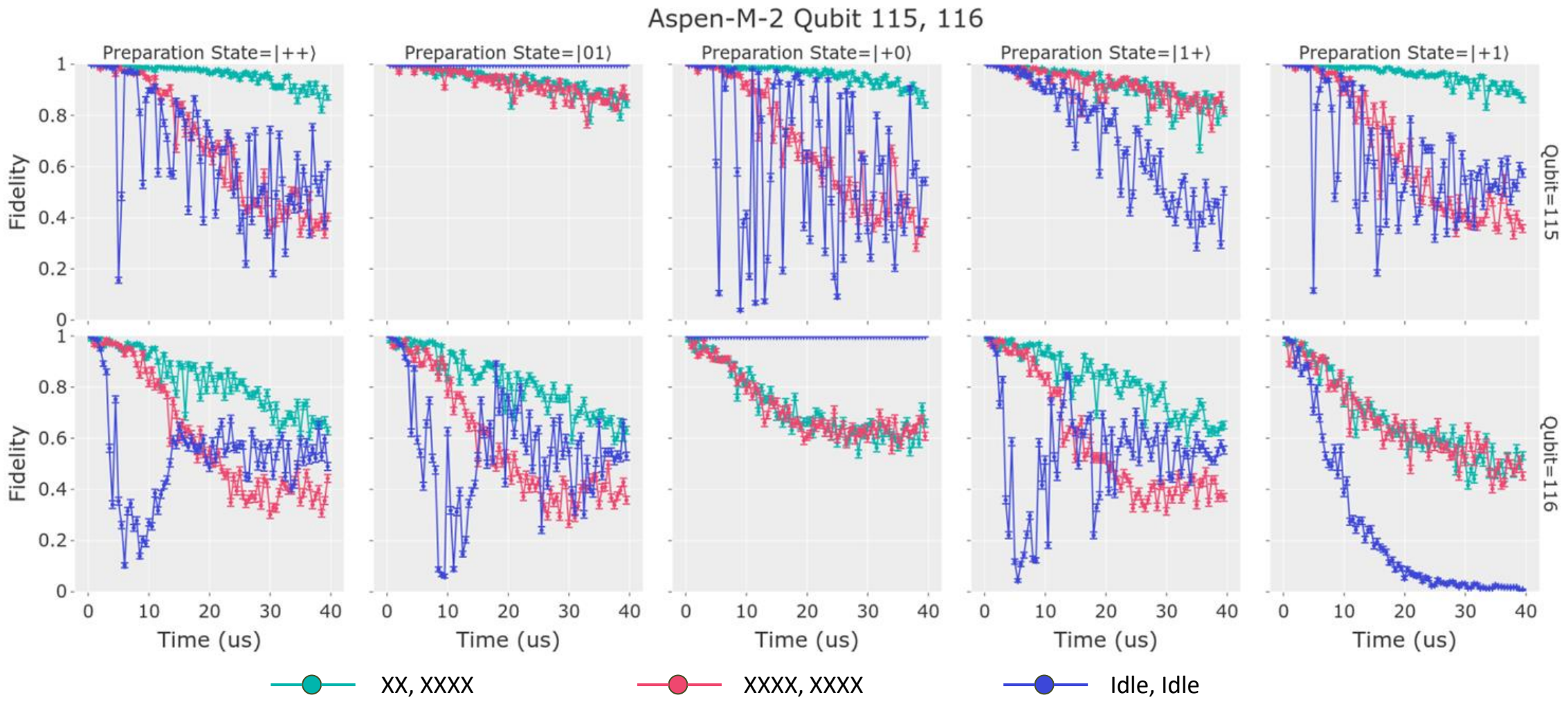




DD Sequence	ZZ Decoupled
XXXX, XXXX	✗
XX, XXXX	✓

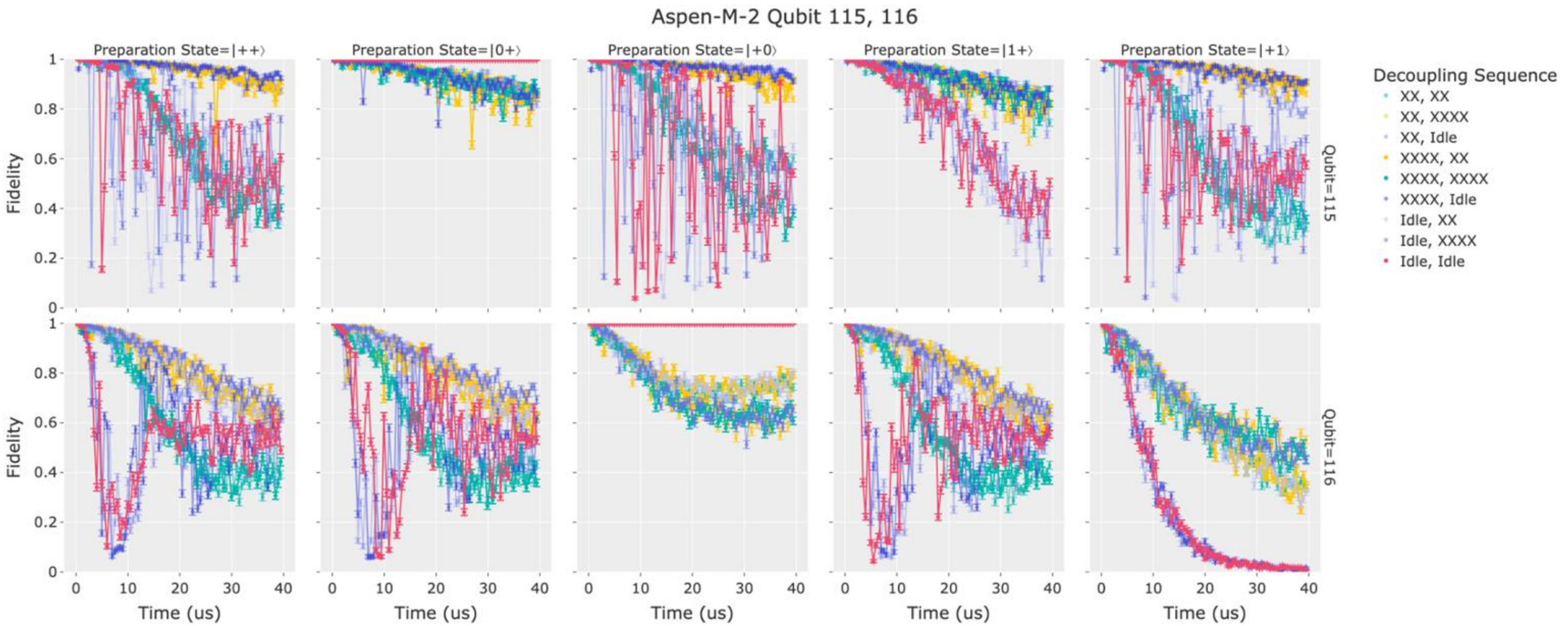
The frequency-mismatched DD sequences suppress the crosstalk effect on both qubits.

Results: different initial states



For each DD sequence, we run on a complete set of initial states, hence a state-tomography-like experiment.

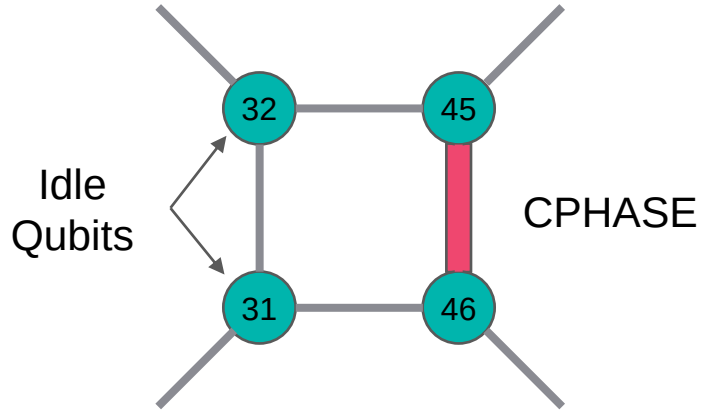
Results: different initial states



Application to algorithmic circuits

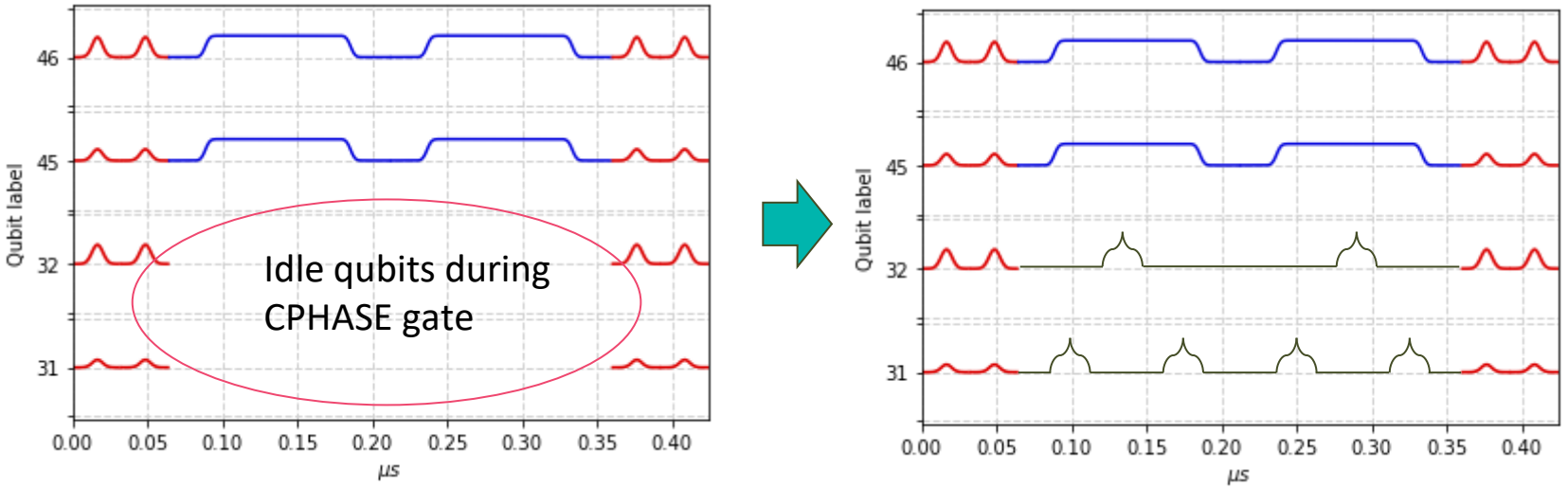
STEP 1: DECOUPLE IDLE QUBITS DURING 2-QUBIT GATES

- During 2-qubit gates, other qubits might be idle and can be protected with DD.
- This can improve overall circuit fidelity.



Bare circuit (without DD)

Circuit with DD

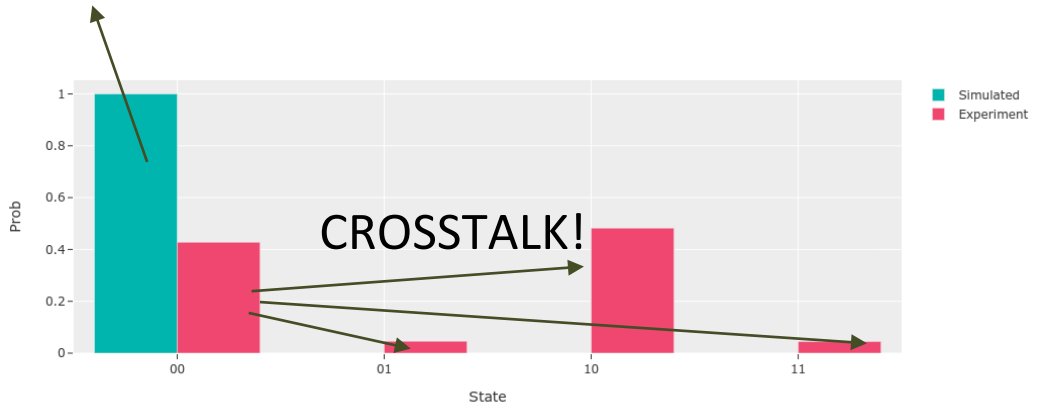


Application to algorithmic circuits

STEP 2: CIRCUIT LAYER FIDELITY IMPROVEMENT

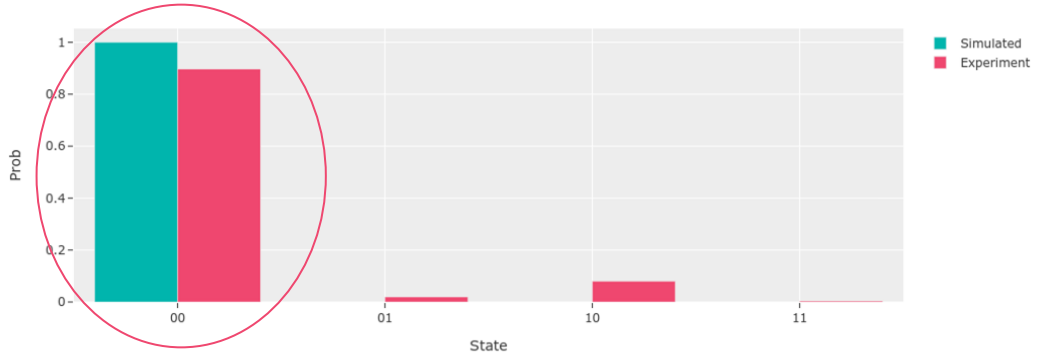
Should always measure |00>... But we don't

Bare circuit

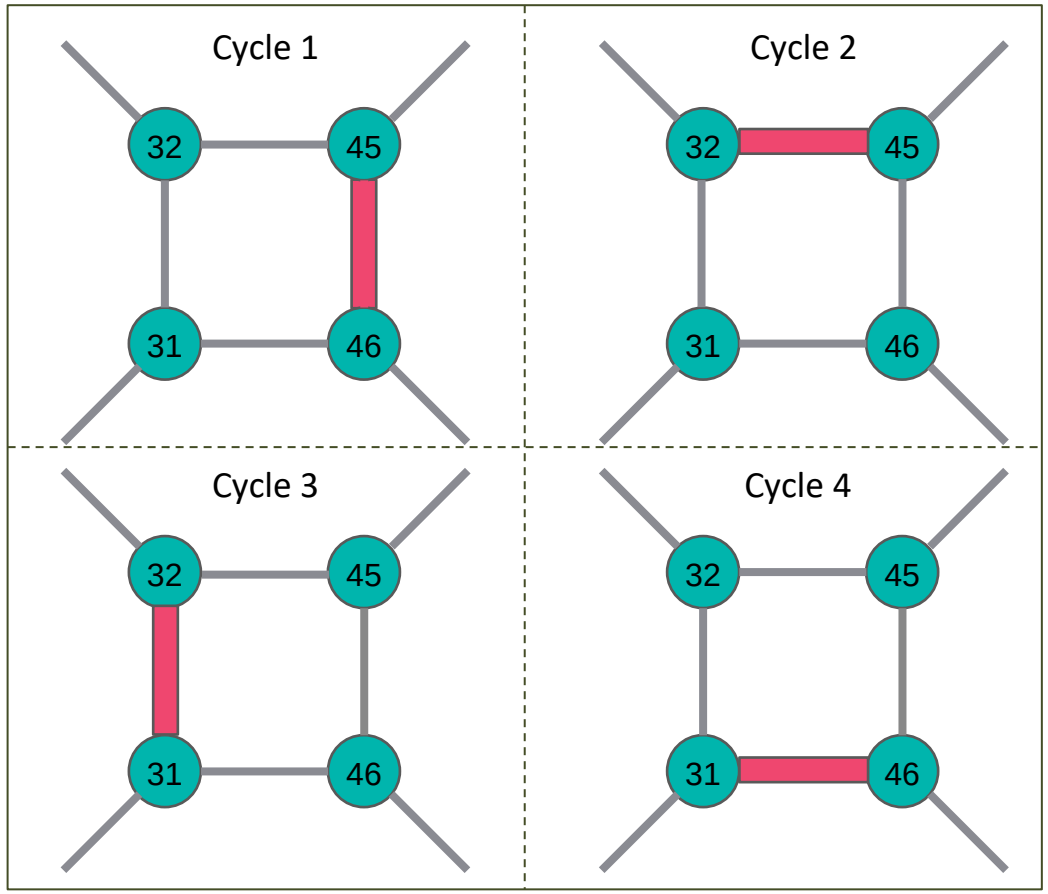


Much better!

Circuit with DD

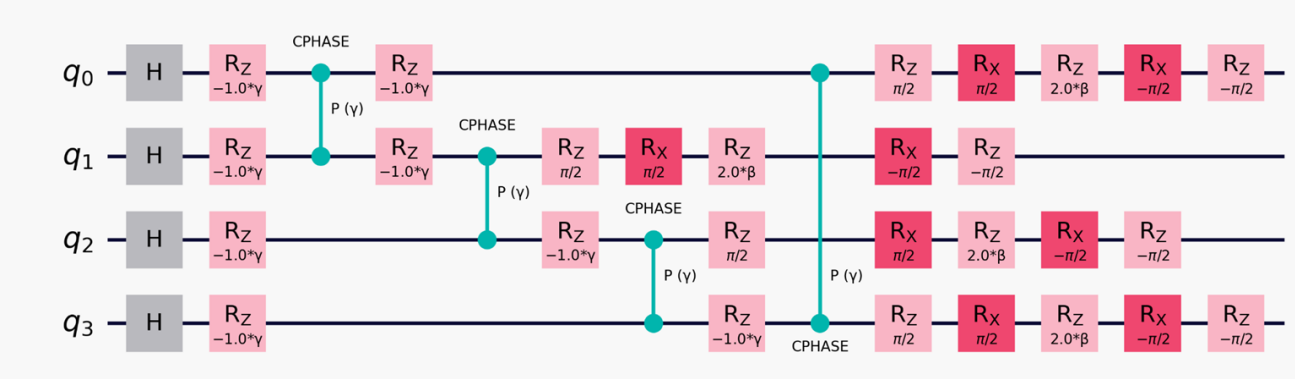


QAOA cost layer: 4 cycles, with 2 idle qubits in each cycle.



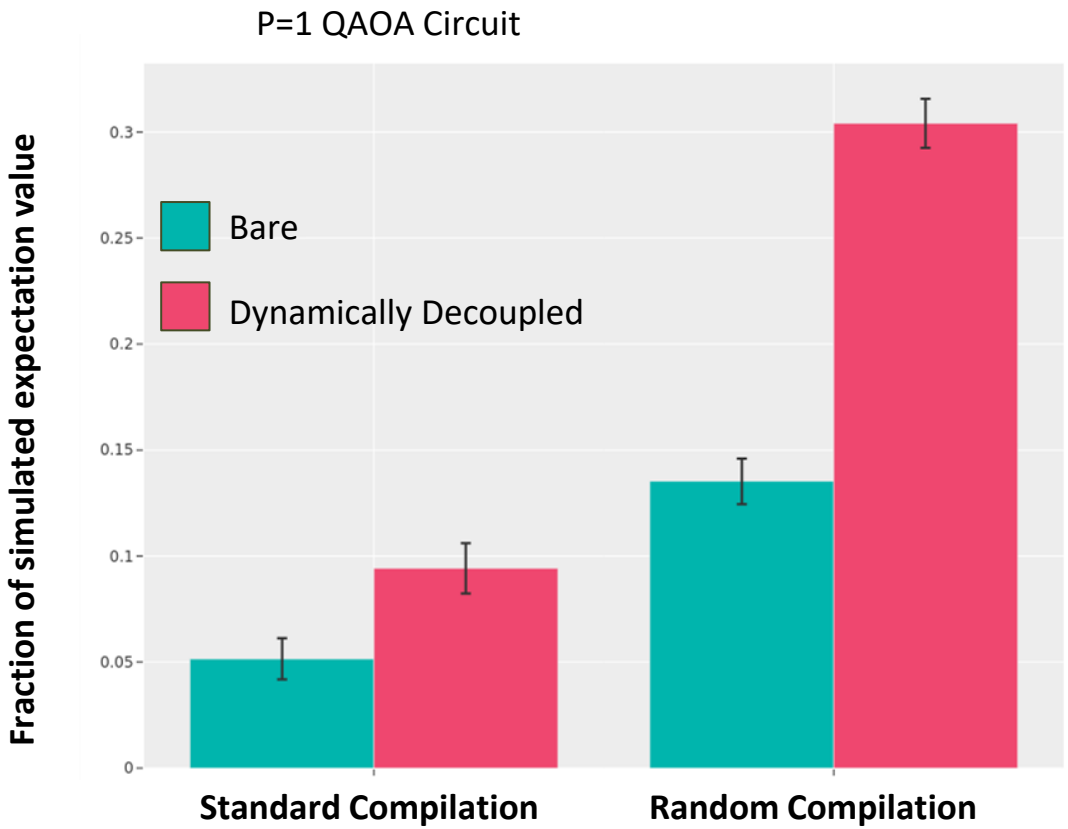
Application to algorithmic circuits

STEP 3: QAOA CIRCUIT IMPROVEMENT



- Updated metrics better suited for circuits.
- Additional error suppression technique (random compilation) combines with DD for even better performance.

VERY PROMISING RESULTS!



Conclusions and future work

- Frequency-mismatched DD sequences suppress ZZ crosstalk between neighbor qubits without sacrificing single-qubit coherence.
- These sequences show promising results for improved fidelity in algorithmic circuits.

NEXT STEPS

- Engineering the DD sequences of the future!
  - With individual qubit control, it is possible to decouple any static interaction.
- Scale to larger circuits.
- Further adjust frequencies to suit magnitude of crosstalk between different qubit pairs.
  - Consider pulse error accumulation and magnitude of ZZ coupling.
- Experimentally explore residual interaction leftover after decoupling ZZ.
  - Lots of other noise channels to decouple!

Thank you!

Questions?

Are you a grad student who would like to intern at NASA QuAIL*?
USRA is always hiring!
Reach out!

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*Quantum Artificial Intelligence Laboratory

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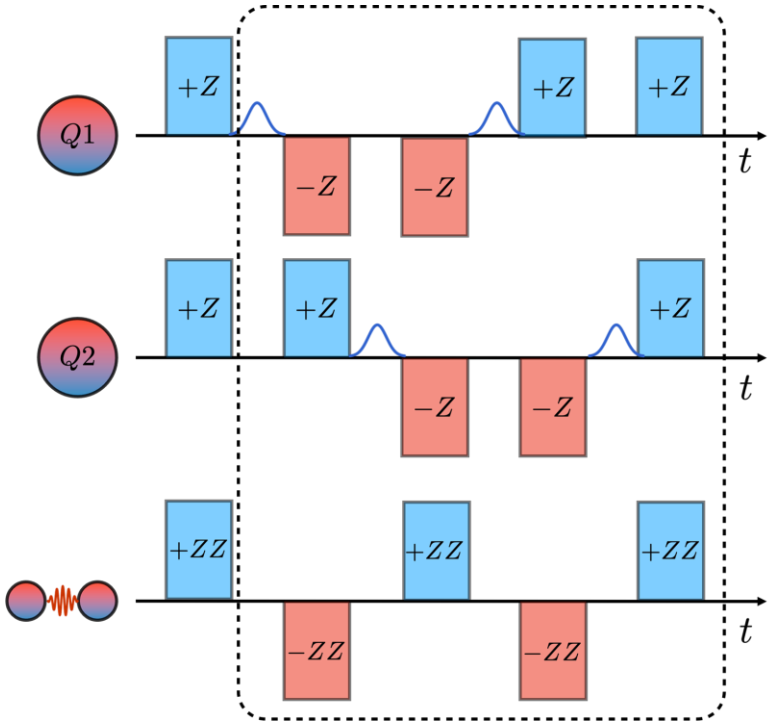
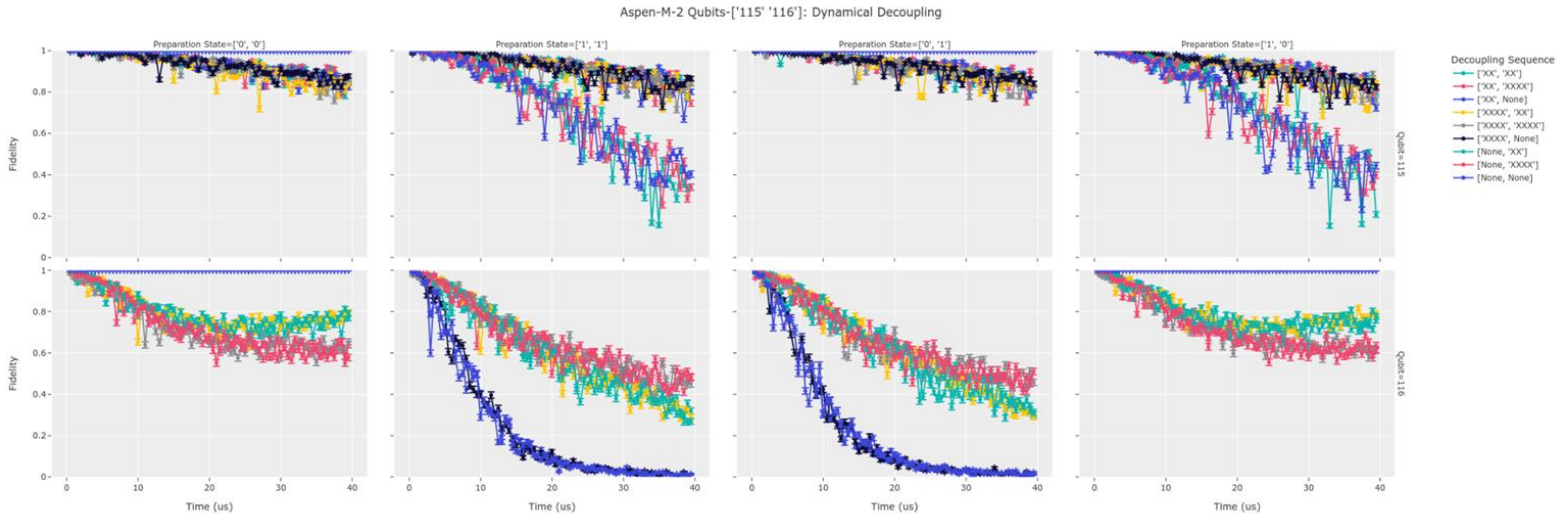
Back-up


Q1
Q2
+Z
−Z
+ZZ
−ZZ
t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Preparation State=['1', '1']
Preparation State=['0', '1']
Preparation State=['1', '0']
Fidelity
Time (us)
Qubit=115
Qubit=116
Decoupling Sequence
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